



Semileptonic and leptonic decays of B hadrons

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1. INTRODUCTION

Exclusive semileptonic and leptonic decays of B mesons are affected far less than hadronic decays by uncertainties due to strong interactions of quarks. As such, they are the modes of choice for measurement of the CKM matrix elements V_{cb} and V_{ub} . Nonetheless, past calculations of the decay widths have relied on phenomenological models such as the non-relativistic quark model and QCD sum rules to describe the behavior of the b and spectator quarks. The reliance on models can be lessened or eliminated by using heavy-quark symmetry arguments and/or lattice QCD. Both have made sufficient progress in recent years to kindle hope for smaller theoretical uncertainties in future determinations of CKM matrix elements. This optimism must be tempered by the experimental realities, as this comparison with theory will require the measurement of helicity-dependent form factors as a function of q^2 .

Interest is currently focused mainly on those decays for which prospects appear to be good, both for experimental measurement and theoretical certainty. We first list the modes and discuss the theoretical motivations. We then consider the prospects for experimental measurement of these modes, making projections five years into the future (1998).

2. THEORETICAL PROSPECTS

From a theoretical standpoint, (semi)leptonic decays may be organized as follows, where “ D ” refers to D_u , D_d , or D_s mesons:

1. Leptonic modes ($\tau\bar{\nu}$, $\mu\bar{\nu}$)
2. Three-body $b \rightarrow c$ modes ($\{D/D^*/D^{**}/\Lambda_c\}l\bar{\nu}$)
3. Four-body $b \rightarrow c$ modes ($\{D/D^*\}\{\pi/K\}l\bar{\nu}$)
4. Three-body $b \rightarrow u$ modes ($\{\pi/\rho/\eta/\omega/N\}l\bar{\nu}$)
5. $b \rightarrow u$ modes for the study of ρ - ω interference ($\pi\pi l\bar{\nu}$)

The width of purely leptonic decays of B_q ($q = u, c$) is proportional to $|V_{qb}|^2 f_{B_q}^2$, where f_{B_q} is the decay constant, and $|V_{qb}|$ is the CKM matrix element of interest. The

tauonic mode suffers least from helicity suppression. These and the three-body tauonic modes are also of interest, because they are sensitive to some proposed extensions of the standard model. For example,¹ charged Higgs boson effects may enhance $B \rightarrow \tau \bar{\nu}$, $\mu \bar{\nu}$ above standard model expectations of order 10^{-4} and 4×10^{-7} , respectively. The ratio $BR(B \rightarrow \mu \bar{\nu})/BR(B \rightarrow \tau \bar{\nu}) \simeq 0.0045$ would remain unchanged. Conversely, the interference effect with charged current contributions may be destructive, and rates of purely leptonic modes may well be much below standard model expectations.

The bulk of the interest is in measurements of semileptonic decays to determine $|V_{cb}|$ and $|V_{ub}|$. This analysis requires theoretical calculations of form factors, which depend on $y = v \cdot v'$, where $v^{(\prime)}$ is the velocity of the initial (final) state meson. Below we briefly discuss theoretical prospects for obtaining the form factors. We discuss $|V_{cb}|$ and $|V_{ub}|$ separately, because the theoretical issues differ somewhat for the two cases. For more details see the contributions of Grinstein for HQET and Kronfeld for lattice QCD in these Proceedings.

2.1 Decays involving V_{cb}

Heavy-quark symmetry normalizes the form factors for heavy-to-heavy transitions such as $B \rightarrow D^{(*)} l \nu$ and $\Lambda_b \rightarrow \Lambda_c l \nu$ at zero recoil $y = 1$ in the infinite mass limit. Heavy-quark effective theory (HQET) classifies the $1/m^n$ corrections. For a generic form factor $f(y)$

$$f(1) = 1 + c_1 \frac{\bar{\Lambda}}{m_c} + c_2 \frac{\bar{\Lambda}^2}{m_c^2} + \dots, \quad (1)$$

where $\bar{\Lambda} = m_D - m_c$ and the c 's are coefficients of order unity which are independent of m_c or have at most a logarithmic dependence on m_c . HQET does not, however, predict these coefficients. In the special case $B \rightarrow D^* l \nu$, symmetry considerations show that c_1 vanishes.² This means that normalization at the point of zero recoil for this decay is known up to corrections that are of order $\bar{\Lambda}^2/m_c^2$. This allows for model-independent measurement of V_{cb} with small theoretical errors.

Estimating the size of the corrections is important for determining the theoretical uncertainty on the determination of V_{cb} . For this, one must turn to models or lattice QCD. Until now calculations have been performed with QCD sum rules, relativistic quark models and non-relativistic quark models. The first goal of the models is to predict the constant $\bar{\Lambda}$. Calculations in QCD sum rules estimate $\bar{\Lambda} = 500 \pm 100$ MeV,³ while the non-relativistic quark model indicates that $\bar{\Lambda}$ should just be the constituent mass of the light quark, *i.e.*, $\bar{\Lambda} = m_{u,d} \simeq 300$ MeV.⁴ The relation $\bar{\Lambda} = m_D - m_c$ means that the value of $\bar{\Lambda}$ affects both the numerator and the denominator in the expression $\bar{\Lambda}^2/m_c^2$. The difference in the estimated size of the theoretical uncertainty on $|V_{cb}|$ from $B \rightarrow D^* l \nu$ is therefore around 4%.

More theoretical work is being done to further understand these corrections. Although heavy-quark effective theory is a valuable tool, more experience is needed before one will know whether the $1/m$ expansion is quantitatively reliable for charm. Measurements of the decays $B \rightarrow D l \nu$, $B_s \rightarrow D_s^{(*)} l \nu$ and $\Lambda_b \rightarrow \Lambda_c l \nu$ will be needed to carry out these tests.

Lattice QCD can also be used to calculate the form factors directly. The lattice calculations are most reliable for y near 1, the same the kinematic point as in HQET. The limitations of the lattice are time and computer power, and it is unlikely that direct calculations will soon improve on the 4% uncertainty expected from applying HQET. In the next 5 years, the matrix element for $B \rightarrow D^* l \nu$ at the endpoint should be calculable to ~ 5 –10%. On the other hand, a lattice calculation of $\bar{\Lambda}$ can probably be done more reliably than

in the models. Lattice QCD can also be used at $y > 1$ and provide a valuable cross-check with the experimental y dependence.

2.2 Decays involving V_{ub}

As mentioned above, the leptonic decay of the B can yield V_{ub} , given f_B . Because of the low helicity-suppressed rate, however, semileptonic decays are more feasible. In particular, at $y \approx 1$ the decay $B \rightarrow \rho l \nu$ is especially promising, because only one factor survives and the phase-space suppression is less than for $B \rightarrow \pi l \nu$.

To date, determinations of $|V_{ub}|$ have used inclusive semileptonic decays. There are calculations based on perturbative QCD that predict inclusive $b \rightarrow u l \nu$ rates⁵, and different quark models that predict exclusive transitions (and their sum), including the full lepton spectrum.⁶ Unfortunately, these calculations disagree mainly at the endpoint, which is precisely where measurements are free of background from $b \rightarrow c$ transitions. Hence, the models are contradictory in the kinematic region where the experiment is feasible. To avoid the reliance on models one must study exclusive semileptonic decays and use HQET and or lattice QCD.

Semileptonic form factors for $B \rightarrow \{\pi, \rho\}$ cannot be pinned down with heavy-quark symmetry, because the final state hadron consists only of light quarks. One can, however, use heavy-quark symmetry to relate B and D decays into the same light hadron. Including α_s corrections from short-distance QCD and $1/m$ corrections from HQET one finds

$$\frac{A_1^{B \rightarrow \rho}(1)}{A_1^{D \rightarrow \rho}(1)} = 1 + c_l \log \frac{m_b^2}{m_c^2} + c_1(\mu) \left(\frac{1}{m_c} - \frac{1}{m_b} \right) + \dots \quad (2)$$

In a constituent quark model, one finds numerically:⁷

$$\frac{A_1^{B \rightarrow \rho}(1)}{A_1^{D \rightarrow \rho}(1)} \simeq 1.15 \pm 0.01 \pm 0.04, \quad (3)$$

where the first uncertainty is proper of the model parameters and the second is due to the uncertainty in m_c . One consequently finds for the differential rates at $y = 1$:

$$\frac{d\Gamma(B \rightarrow \rho l \nu)/dy}{d\Gamma(D \rightarrow \rho l \nu)/dy} \Big|_{y=1} \approx 22 \cdot \left| \frac{V_{ub}}{V_{cd}} \right|^2 \times (1 \pm 0.07). \quad (4)$$

Although this ratio is predicted at the 7% level, it will be difficult to measure numerator and denominator experimentally, since both rates have vanishing phase space at $y = 1$. An extrapolation to points $y > 1$ will be necessary, but the extending the calculations to those points would be less reliable.

Lattice QCD calculations can calculate the form factors for $B \rightarrow \rho l \nu$ and $B \rightarrow \pi l \nu$ directly. Although no calculations of B decay form factors have yet been carried out, experience from the light hadron spectrum, the B decay constant, and K and D form factors suggests that a combined error of $\sim 15\%$ will be attainable in a year or so. Within five years, the uncertainties may be as small as 5–10%. As with the HQET, the calculations are most reliable at the endpoint $y = 1$, with some deterioration for $y > 1$. As with our estimates for $B \rightarrow D^{(*)} l \nu$ form factors, these estimates do not include estimates of the error from the

quenched approximation. It is still somewhat of an open question, how well the quenched approximation performs as a phenomenology. Nevertheless, this piece of B physics is the one most likely to profit from lattice QCD.

3. EXPERIMENTAL CONSIDERATIONS

For our five-year projections, we consider existing facilities of three types, e^+e^- symmetric colliders at the $\Upsilon(4S)$ (CESR), e^+e^- colliders at higher energies (LEP) and $p\bar{p}$ colliders at high energy (Tevatron). SSC is beyond this time scale, but it is reasonable to assume that the FNAL environment is most applicable; the number of b events collected by a generic detector after one year of running at the SSC is estimated to be two orders of magnitude higher than the projected number for FNAL. Other possibilities not considered are e^+e^- collisions just above B_s or Λ_b threshold and high energy fixed target facilities. The three facilities considered differ greatly in nearly all of the many factors which determine the accuracy of each measurement: numbers of events, event selection efficiencies, and types and quantities of expected background. We discuss first the many general considerations which were used as input to our evaluation and then the specific results used to make our projections. Some of the projected estimates depend on Monte Carlo simulations for crucial detector components which are not yet built.

The number of events produced is determined by the cross section and integrated luminosity. The number remaining after all triggering and analysis requirements depends on other factors, such as event particle multiplicities, the presence of other b -hadron decays which can enter signals, and energy and angular distributions of b -hadrons. In $p\bar{p}$ collisions the distribution peaked at small angles, so that a large fraction of produced b -hadrons fall outside the acceptance of the existing detectors. We consider only the portion which has been observed at CDF, which is estimated to be $\sim 20\%$ of the total. The five-year projections of integrated luminosity, numbers of b -hadrons produced within detector acceptances, and estimated mean and transverse momenta of those b -hadrons are given in Table I.

Table 1. Projected integrated luminosity (1998), numbers of b -hadrons produced within detector acceptances, and mean and transverse momenta for the three facilities considered.

Facility	$\int L dt$	N_{B_d}	N_{B_u}	N_{B_s}	N_{Λ_b}	N_{B_c}	$\langle p_B \rangle, \langle p_B^T \rangle (\text{GeV}/c)$
CESR	20 fb^{-1}	2×10^7	2×10^7	0	0	0	0.3, 0.3
LEP	100 pb^{-1}	8×10^5	8×10^5	2×10^5	2×10^5	8×10^2	35, 25
FNAL	1 fb^{-1}	8×10^9	8×10^9	2×10^9	2×10^9	8×10^6	10-15, 10-15

Detection efficiencies will also vary by mode, depending on the types and number of particles required for reconstruction. It is assumed that the detectors used will be those currently in place at the three facilities, with some upgrades. For LEP and FNAL we assume capabilities for high resolution vertex reconstruction, projected in the plane perpendicular to the beam ("2-d") for LEP and in three dimensions ("3-d") for FNAL (the detector assumed for FNAL is not yet in place, although a "2-d" silicon-based detector ran successfully during the last collider run). It is assumed that detection of π^0 at momenta below 1 GeV/c is possible only at CESR and that none of the detectors will have hadron identification for momenta above 1 GeV/c.

Backgrounds to signals can originate from random combinations of particles or from nonrandom sources. The rate of random accidental candidates depends on event particle multiplicity. Because the presence of a neutrino among the decay products introduces a fairly large intrinsic uncertainty in energy-momentum, the resolution of the detector does not in general define the background, *unless* missing energy and momentum measurements are sufficient to further define the neutrino. Such "neutrino detection" is now used for some measurements at CESR and at LEP; at ALEPH, the resolution on visible energy is ~ 3 GeV and is crucial to a search for inclusive $B \rightarrow \tau$ decays. More often, reduction of random background is accomplished through kinematic and vertex requirements. At CESR the B is nearly at rest, so that the neutrino's energy and momentum may be deduced from those of the detected daughters of the semileptonic decay. Requiring that the neutrino mass implied by these be near zero is very effective in suppressing background. At higher energies, the b -hadrons appear in jets and usually carry a large fraction of the jet energy. Requiring candidates to have a high energy and be associated with a jet are then effective discriminators against random background. Another characteristic of b -hadrons at higher energies is their finite decay length, which is measurable with silicon strip detectors. Requiring that a candidate's reconstructed vertex be separated from the event origin favors tracks which are all associated with a single decay and is very effective in reducing the multiplicity of random tracks. Both LEP and FNAL projections rely heavily on precise vertex measurements to reduce backgrounds.

A major consideration for all cases is that of nonrandom backgrounds, where b -hadron decays other than the one under investigation appear in the signal. This type of background is difficult to reduce and may dominate the event sample. An example is the decay $B_u \rightarrow D^0 l^- \bar{\nu}$, which is difficult to distinguish from the more abundant $B \rightarrow D^* l^- \bar{\nu}$ ($D^* \rightarrow D^0 \pi$) where the π is not detected; consequently, a large subtraction of the latter's contribution is required. An advantage of studying $\Upsilon(4S)$ decays is that B_u and B_d are produced with no B_s and Λ_b . To balance this, vertex reconstruction capability in higher energy machines may enable significant reduction of backgrounds from modes with one or more additional daughters by rejecting those candidates with additional tracks consistent with originating at its vertex.

Another potentially important tool, particularly for distinguishing feeddown from higher B states, is particle identification. In the facilities considered here, such a capacity will probably not be implemented in the next few years. This question was therefore not studied in detail here.

4. EXPERIMENTAL PROJECTIONS

4.1 Leptonic decays and decays with τ

Pure leptonic and semitauonic decays are difficult to measure because of large missing energies. Both are also relatively rare, the semitauonic due to reduced phase space and the leptonic due to helicity suppression.

Searches for $B_u \rightarrow \tau\nu$ and $B_u \rightarrow \mu\nu$ at CLEO have thus far yielded no positive results. The 90% confidence upper limits on branching fractions from 0.9 fb^{-1} of data are 0.013 and 2.0×10^{-5} .⁸ The Standard Model predictions are 10^{-4} and 4×10^{-7} , respectively. The branching fractions which may be probed with additional data depends somewhat on the level of backgrounds which are found – tighter cuts may be necessary. With 20 fb^{-1} of integrated luminosity, we estimate sensitivities of $\sim 10^{-3}$ and $\sim 10^{-5}$, respectively. A feasibility study at ALEPH⁹ yields a preliminary conclusion that it is possible with the projected luminosity to probe the leptonic decays $B \rightarrow \tau\bar{\nu}, \mu\bar{\nu}$ to branching fractions of 10^{-4} . This should allow the full range of possible enhancements from charged Higgs boson effects to be explored.

At LEP a search for decays $B \rightarrow \tau X$ finds¹⁰ a branching fraction $(2.76 \pm 0.47 \pm 0.43) \times 10^{-2}$. This value is in agreement with the Standard Model and rules out enhancements predicted by some extended models. It is worth emphasizing, however, that charged Higgs boson effects are more enhanced in purely leptonic decays than is possible in semileptonic decays. Although the inclusive $B \rightarrow \tau X$ result is fully consistent with standard model expectations, it does not exclude the possibility of enhancements¹ in $B \rightarrow \tau\bar{\nu}$ and $B \rightarrow \mu\bar{\nu}$.

4.2 Semileptonic decays with V_{cb}

The decay $\bar{B}_{u,d} \rightarrow D^* l^- \bar{\nu}$ is the only mode to date to have been used to measure $|V_{cb}|$ via HQET and is likely to continue its dominant role. The result from 1.65 fb^{-1} of data from CLEO 1.5, ARGUS and CLEO II is $|V_{cb}| = 0.038 \pm 0.003 \pm 0.004$,¹¹ where the first error is statistical and the second systematic, mainly due to the uncertainty in the B lifetime. A simple extrapolation to 20 fb^{-1} of data would give statistical errors around ± 0.0007 . The limiting uncertainty will undoubtedly be systematic, however, mainly from the measurement of the B lifetime. The error here will probably improve by at most a factor of 2 in the next few years, so that the overall error of ± 0.006 may be reduced to ± 0.002 .

At LEP, D^* -lepton correlations and vertex requirements have yielded a signal/background of around five for the decay $\bar{B}_d \rightarrow D^{*+} l^- \bar{\nu}$.¹² The signal quality is similar for other charmed three-body decays. The projected yield is ~ 750 decays $\bar{B}_d \rightarrow D^{*+} l^- \bar{\nu}$, and although this does not appear competitive with CESR, the vertexing capability will enable rejection of such backgrounds as $\bar{B}_d \rightarrow D^{*+} l^- \bar{\nu}$ and $\bar{B}_d \rightarrow D^{*+} \pi l^- \bar{\nu}$, as well as studies of these modes and of $B \rightarrow D l^- \bar{\nu}$. These are important for establishing the relative rates to the different channels, for testing the theory, and for reducing systematic uncertainties. For B_s and Λ_b three-body decays the LEP sample will be an important contribution, with ~ 50 and ~ 150 events, respectively. The 150 events $\Lambda_b \rightarrow \Lambda_c l^- \bar{\nu}$ should give statistical errors on $|V_{cb}|$ which are roughly equivalent to those from current measurements with $B \rightarrow D^* l^- \bar{\nu}$, around ± 0.006 . We note, however, that the absolute normalization of the width may have larger systematic uncertainties, as the production rate of baryons is difficult to establish.

Although at the $p\bar{p}$ collider the fragmentation is softer and background is much higher, Monte Carlo studies indicate that with 3-d vertexing it is possible to achieve a signal/background for the $D^* l^- \bar{\nu}$ mode which is of the same order as that achieved at LEP

with 2-d vertexing.¹³ With the projected luminosities of Table I, the yield would be about twice that at LEP.

Other interesting measurements involve four-body modes calculated via HQET and chiral perturbation theory,¹⁴ such as $\bar{B}_d \rightarrow D^{*+} \pi l^- \bar{\nu}$. These are the backgrounds to $\bar{B}_d \rightarrow D^{*+} l^- \bar{\nu}$ described above, and it appears that they may be measured quite cleanly at LEP.

4.3 Semileptonic decays with V_{ub}

The inclusive $b \rightarrow u$ semileptonic rate of B_u/B_d mesons has been measured with 0.9 fb^{-1} of data at CESR and gives a value for $|V_{ub}|/|V_{cb}|$ of 0.075 ± 0.008 , with theoretical range ± 0.02 .¹⁵ Measurement of exclusive modes is necessary to reduce the theoretical uncertainties. A search for decays $B^- \rightarrow V^0 l^- \bar{\nu}$ where V^0 is either ρ^0 or ω^0 yields a net 2σ excess of candidates.¹⁶ If this is interpreted as a signal, it corresponds to a branching fraction of 1×10^{-4} and is consistent with the inclusive measurement. If we project from this to 20 fb^{-1} of data, the statistical error will be $8 - 25\%$ on the branching fraction and $4 - 13\%$ on $|V_{ub}|$. With such a large data sample, it may be possible to perform the first measurements of form factors.

The projected luminosity at LEP is insufficient for $b \rightarrow u$ measurements. Although no studies are yet available of projections at the Tevatron, it seems unlikely, given the higher backgrounds and results from studies of the charm modes, that there will be a great advantage relative to LEP.

5. CONCLUSIONS

Although semileptonic and leptonic decays are favored for measurement of CKM elements due to their minimal theoretical uncertainty, measurements of $|V_{cb}|$ and $|V_{ub}|$ are currently limited by uncertainties of the theory. Because of new developments with HQET and lattice gauge theories, this situation is likely to change in the next few years, with both theoretical and experimental uncertainties reduced significantly. The new focus is on the semileptonic partial width at points near q_{max}^2 .

The modes involving V_{cb} which are of highest theoretical interest are the vector meson decays ($B \rightarrow D^* l \nu$) and baryon decays ($\Lambda_b \rightarrow \Lambda_c l \nu$). The present experimental uncertainty on $|V_{cb}|$ is around 20%. We expect that in five years the best statistical errors on $|V_{cb}|$ will be better than 2%, from measurements of the decay $B \rightarrow D^* l \bar{\nu}$ at CESR, but that systematic errors will undoubtedly be larger, around 7%; the expected theoretical uncertainty is 4%. LEP and/or the Tevatron may be able to provide important supplementary information on this mode, as they will have better access to the crucial region near q_{max}^2 and better rejection of backgrounds from modes with higher multiplicity. This would serve to reduce the systematic uncertainties. Λ_b measurements will probably be done at LEP, possibly at the Tevatron, but systematic uncertainties may be problematic.

Tests of theories which combine HQET and chiral perturbation theory to describe four-body modes appear to be possible at LEP.

The $b \rightarrow u$ modes are more difficult, both theoretically and experimentally. The leptonic decays $\tau \nu, \mu \nu$ are most clean, from the theoretical standpoint. Taking full advantage of vertexing and missing energy measurements, it appears that LEP will be sensitive to the Standard Model prediction for $\tau \nu$, at a level of 10^{-4} . Experimentally, the semileptonic modes will be more precisely measured, and any progress will probably be made at CESR. We project from inclusive measurements and indications from searches for exclusive decays that statistical errors on $|V_{ub}|$ will be $5 - 15\%$ within five years. The first measurements of

form factors may be possible with such a data sample, and these may be necessary to reduce systematic errors. Present theoretical uncertainties are $\sim 25\%$. Reduction of these to $< 10\%$ may be possible in the next five years.

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